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Blockchain-Based and Multi-Layered Electricity Imbalance Settlement Architecture

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***Abstract*—In the power grid, the Balance Responsible Parties (BRPs) purchase energy based on a forecast of the user consumption. The forecasts are imperfect, and the corrections of their real-time deviations are managed by a System Operator (SO), which charges the BRPs for the procured imbalances. Flexible consumers, associated with a BRP, can be involved in a demand response (DR) program to reduce the imbalance costs. However, running the DR program requires the BRP to invest resources in the infrastructure and increases its operating costs. To limit the intervention of BRP, we implement the DR via a blockchain smart contract. Moreover, to reduce the delay of publication of the imbalance price, caused by the inefficient accounting process of the current balancing markets, a second blockchain is adopted at the SO layer, procuring a fast and auditable credit settlements. The feasibility of the proposed architecture is evaluated over an Ethereum blockchain platform. The results show that blockchains can enable a high automation of the balancing market, by providing (i) the implementation of aggregators with low operating cost and (ii) the timely and transparent access to the balancing information, thus fostering new business models for the BRPs.**

I. Introduction

The massive deployment of intermittent renewable energy resources into the power grids is increasing the amount of energy that the System Operators (SOs) contract on the balancing market in order to match generation and demand in real-time. The imbalance costs can be compensated by including small-scale flexible consumers in the electricity market, but this requires redesign of the market operation, as it currently does not scale with the number of active participants [1].

Fig. 1 depicts the legacy imbalance settlement architecture. Layer 1 includes the SO and the Balance Responsible Parties (BRPs), while layer 2 comprises the consumers associated with the corresponding BRP. At layer 1, the BRPs send the aggregated forecasted generation/consumption to the SO before the period of operations and receive the imbalance cost after it. At layer 2, the BRPs offload the imbalance cost to their consumers, after metering their actual consumption.

The flexible consumers can be incentivized to reduce the procured imbalances by trading their flexibility [2]. However, the costs of coordinating, metering, and accounting the financial positions of the flexible consumers may restrain the BRPs to implement such mechanisms [3]. In this respect, the advent of blockchain protocols is seen as an enabler of low-cost flexibility markets [4]. The low cost stems from the fact that, in a blockchain, the state of the system is stored in a tamper-proof decentralized database [5], removing the need of centralized coordination.

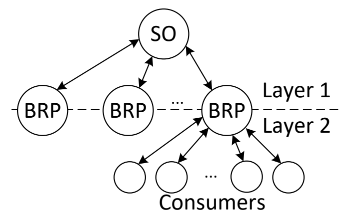


Fig. 1. Imbalance settlement architecture.

In this paper, we present a blockchain-based scheme, based on the Ethereum protocol [5] and implemented at layer 2 of the imbalance settlement architecture, in which flexible consumers trade their flexibility to minimize the BRP's imbalance volume. The flexibility is provided by a demand response (DR) program in which the flexible consumers adjust their consumptions according to the imbalance volume. The only information required by the blockchain-based scheme from the BRP is the imbalance price, which depends on the imbalances produced by all the BRPs and the volume of imbalances to counteract. Subsequently, we show that the scheme is challenged by the delay of the accounting processes which can be significant; e.g., the imbalance price is published by the accounting authorities in Germany with a delay of one month [6]. Therefore, the BRP can only provide its estimated value to the layer 2 market, which affects its efficiency. This motivates us to also use a blockchain at layer 1 and automatize the task of the accounting authorities, which is another contribution of the paper.

The presented results show that, at layer 2, the scheme reduces the flexible consumers' cost, which is function of the amount of flexibility, imbalance price and its estimation error. At the same time, the use of a smart contract keeps the operating cost for the BRP low, making the solution economically profitable. Finally, the presented approach reduces the imbalance settlement delay at layer 1, and consequently improves the performance of the layer 2 markets.

The paper is organized as follows. Section II provides an introduction to balancing markets, blockchains and smart contracts. Section III describes the system model, and Section IV elaborates the design of the blockchain platform. Section V presents the results and Section VI concludes the paper.

II. Background

A. Design of electricity market

The criteria and trade-offs of electricity market design are discussed in [7]. In this paper, we focus on the importance of market facilitation in terms of provision of electricity at the least cost. The market facilitation criterion includes equal availability and timeliness of information to all market participants. In the context of the balancing market, the timely publication of the imbalance price is particularly critical, as it provides the incentives to market players to reduce their financial exposure. However, this principle is challenged by the delayed publication of the imbalance price and volumes, due to the inefficient accounting process, caused by the complexity of the system [6]. The impact of information delay has been empirically studied, by observing the various strategies adopted by market players in countries where this delay is different, i.e. Germany and the Netherlands [8].

B. Blockchain and smart contracts

A blockchain protocol leverages on cryptographic primitives to securely replicate a database, that stores the states of accounts, within a network of agents. The state of an account consists of its accumulated credit and a general purpose storage memory. To read or modify the state of an account, one can only use pre-defined functions. Together, the state and its set of functions form a data structure called *smart contract* [5]. The smart contract is deployed in the blockchain database by its owner. To incentivize agents to store a copy of the database, every modification of the contract, called a "transaction", is subject to the payment of a fee, under the form of credit. The fee increases with the portion of account's storage memory that is modified. This also discourages unnecessary updates to the contract, i.e. spamming attacks. Finally, to keep the copies of the database consistent, the history of updates is stored as a tamper-proof concatenated list, known as a blockchain. To avoid proliferation of different lists, only one agent can apply the modifications in each time period, by appending new information blocks. This agent can be elected according to various mechanisms, e.g. the proof-of-work [5], while the appended blocks contain collection of transactions that do not conflict with those already included in previous blocks.

C. Blockchain applications in the smart grid

Recently, there has been a rising interest in the area of blockchain applications for smart grids [9]–[12]. The basic applications are the peer-to-peer energy trading [9], where the accounts' states are simply used as financial ledger, or the certification of origin [10], in which generators attest their production on the blockchain. More advanced applications use a smart contract to supervise optimization problems [11], or to implement distributed auctions in microgrids (MGs) [4]. It has also been shown that a smart contract can be used to track the control history of Distributed Energy Resources (DERs) and thus establish fairness [12].

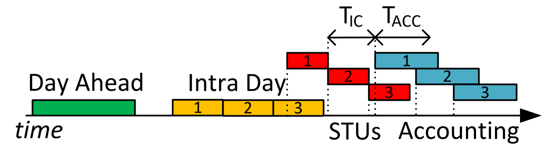


Fig. 2. Time organization of the operations.

III. System model

In the electricity markets, there are several operation periods during a day, called *schedule time units (STUs)*, or *balancing periods* [7], see Fig. 2. Each period corresponds to a generation and consumption plan. We model a simplified electricity market in which the energy, relative to a STU, can be traded in two different stages: day ahead (DA) and intra-day (ID), see Fig. 2, which are presented in the following text.

The agents in the system are: at layer 1, a SO and the BRPs, and, at layer 2, a BRP and the associated flexible and inflexible consumers, see Fig. 1.

A. Layer 2

A set $\mathcal{U}$ of U flexible consumers and a set $\mathcal{V}$ of V inflexible consumers are associated to a BRP. A consumer $v \in \mathcal{V}$ is characterized by a load profile modeled as a household, and sporadically communicates with the BRP, to report its metered consumption in each STU, which is q_v kWh.

The flexible consumer $u \in \mathcal{U}$ is modeled as an electric vehicle (EV) charging station, cf. [13]. The maximum amount of energy delivered to u in a STU is Q_u kWh, but u can decide to curtail the energy absorption to q_u, $Q_{\min,u} \leq q_u \leq Q_u$, by decreasing its power acceptance rate at the expense of a longer charging time. To simplify the scenario, we assume that $Q_{\min,u} = Q_{\min}$ and $Q_u = Q$, $\forall u \in \mathcal{U}$, and assume a linear utility function:

$$f(q_u) = \pi_u q_u,$$

where π_u is the marginal utility of u, representing its willingness to vary the energy absorption.

Finally, the BRP owns a renewable energy source (RES) that produces Q_{w} kWh in a STU.

B. Layer 1

The SO contracts the balancing energy from a pre-qualified set of Balance Service Providers (BSPs) [6]. We assume that the SO receives enough offers from BSPs to safely operate the grid, and we only focus on the BRPs wholesale market.

In the DA market stage, see Fig. 2, energy provisions are contracted for the entire next day, based on estimated values; these values are indicated with the tilde symbol in the rest of the paper, to distinguish them from their actual values. The BRP estimates the load profile of the V households, and the energy produced by the RES, $\tilde{Q}_{\mathrm{w}}$. We assume that the estimation error of the consumers' profile and RES production are Gaussian, with zero mean and standard deviations σ_{h} and σ_{w}, respectively. At the closure of the DA market, each BRP sends to the SO the forecasted aggregated consumption/generation for each STU. In a generic STU, it is:

$$\tilde{q} = \sum_{v\in\mathcal{V}} \tilde{q}_v + \sum_{u\in\mathcal{U}} \tilde{q}_u - \tilde{Q}_{\mathrm{w}},$$

where the terms on the right correspond to inflexible consumers, flexible consumers, and energy source, respectively.

During each STU, see Fig. 2, the SO is in charge of the real-time balancing. In this phase, it monitors the grid and sends control commands to the BSPs, activating their offers.

After each STU, the BSPs are rewarded for the provision of the balancing service and the BRPs charged for the procured imbalances. The metered absorbed energy by the BRP in a STU is:

$$q = \sum_{v\in\mathcal{V}} q_v + \sum_{u\in\mathcal{U}} q_u - Q_{\mathrm{w}}.$$

Thus, the imbalance volume procured by the BRP in a STU is $q - \tilde{q}$; when $q - \tilde{q} > 0$, the SO provided down-regulation, whereas in the opposite case, up-regulation.

As an example, Fig. 3 shows the load curve sent from the BRP to the SO for a day, in a scenario with high penetration of EVs. The integral of the difference between the forecasted consumption and the metered one constitutes the imbalance volume produced by the households.

C. Imbalances accounting

The accounting authority collects the measurements of absorbed energy from sensors, which is an operation that requires T_{IC} minutes, see Fig. 2. The accounting process, which serves to define the imbalance price and volumes of each BRP, has duration of T_{ACC} minutes, and is described in the following text. To simplify the presentation, we assume that the balancing cost associated to a BRP, relatively to a STU, depends on the imbalance price and volume as:

$$J_{\mathrm{BM}} = \pi^\star \cdot (q - \tilde{q}). \tag{1}$$

The imbalance price $\pi^\star$, in this work measured in €/kWh, is formulated differently in each country, to provide the right incentives to the specific markets [6], [14].

All BRPs receive the information about the real imbalance price with a delay of $T_{\mathrm{IC}} + T_{\mathrm{ACC}}$ minutes from the end of the corresponding STU, i.e. the delay includes metering delay and accounting delay [15]. The BRPs contract energy for a STU by using an estimate of the imbalance price, denoted by $\tilde{\pi}^\star$, which is based on the historical record of the actual imbalance price. The estimation error $\pi^\star - \tilde{\pi}^\star$ is affected by the publication delay; we remark that this error has only been empirically characterized in literature, cf. [8] and that it depends on the adopted estimation technique, cf. [16], [17]. In this work, we assume that the BRP disposes a Gaussian estimate of $\pi^\star$, i.e. $(\pi^\star - \tilde{\pi}^\star) \sim \mathcal{N}(0, \sigma_{\mathrm{BM}}^2)$. It is reasonable to assume that σ_{BM} increases with the publication delay.

The inflexible consumer $v \in \mathcal{V}$ is charged according to a fixed price, proportionally to its consumption:

$$J_v = (\pi_{\mathrm{C}} + \pi_{\mathrm{G}}) \cdot q_v, \tag{2}$$

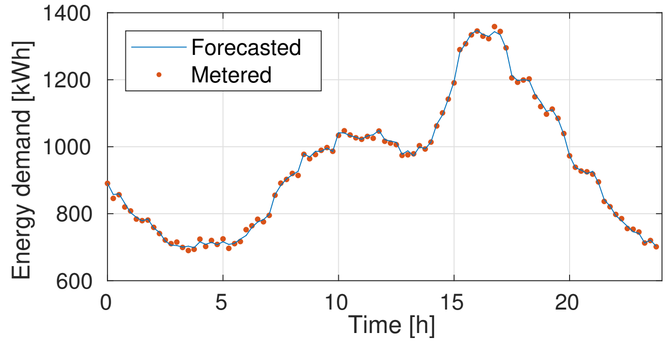


Fig. 3. An example of demand plan (households and EVs associated with a BRP) and its realization. Each marker corresponds to a STU.

where π_{C} €/kWh is the price of electricity and π_{G} €/kWh is the price for the imbalances. The adoption of fixed price for the imbalances avoids the exposition of v to the variable cost (1), but also contains a margin for the BRP.

The flexible consumer $u \in \mathcal{U}$ is charged for the absorbed energy, similarly to the inflexible one, but is exposed to the imbalance cost, proportionally to its consumption:

$$J_u = \left(\pi_{\mathrm{C}} + \pi^\star \cdot \frac{q - \tilde{q}}{|\sum_{u\in\mathcal{U}} q_u| + |Q_{\mathrm{w}}|}\right) \cdot q_u. \tag{3}$$

The BRP earns from selling the electricity and from the margin on the imbalances of inflexible consumers, and is charged of the imbalances caused by the RES. Its resulting imbalance cost is:

$$J_{\mathrm{BRP}} = -\,\pi_{\mathrm{C}} \cdot \left(\sum_{v\in\mathcal{V}} q_v + \sum_{u\in\mathcal{U}} q_u\right) - \pi_{\mathrm{G}} \cdot \sum_{v\in\mathcal{V}} q_v + \pi^\star \cdot \frac{q - \tilde{q}}{|\sum_{u\in\mathcal{U}} q_u| + |Q_{\mathrm{w}}|} \cdot Q_{\mathrm{w}}. \tag{4}$$

D. Flexibility market: Demand Response (DR) program

The implementation of a flexibility market at layer 2 is motivated by the fact that before the ID closure time, the BRP amends its estimation of power generated by the RES, thanks to improved forecast. Specifically, the BRP obtains the information about its estimation error $Q_{\mathrm{w}} - \tilde{Q}_{\mathrm{w}}$. Therefore, it can reduce the cost in (1) by buying or selling electricity on the ID market, see Fig. 2, or by internally balancing it.[1] In this paper, we investigate the second option. The flexibility is procured by a DR program that is permitted to curtail the energy delivered to the EV stations, when the RES is under-producing. We note that previous works showed the potential of this application [18].

As the amount of energy procured by the DR program is the difference between the maximum and actual absorption from flexible consumers, i.e. $UQ - \sum_{u\in\mathcal{U}} q_u$, the normalized amount of energy *not* compensated by the program is:

$$Q_{\mathrm{DR}} = \frac{(Q_{\mathrm{w}} - \tilde{Q}_{\mathrm{w}}) - (UQ - \sum_{u\in\mathcal{U}} q_u)}{Q_{\mathrm{w}} - \tilde{Q}_{\mathrm{w}}}, \tag{5}$$

[1] In a scenario where the BRP does not receive any forecast information, it can still speculate on the sign of imbalance price, see [17].

defined only for $Q_\text{w} \neq \tilde{Q}_\text{w}$. The BRP allocates a fraction α, $0 \leq \alpha \leq 1$, of the amount payed by inflexible consumers to cover the imbalances, i.e. $\pi_\text{G} \sum_{v\in\mathcal{V}} q_v$ (second term of (2)), to incentivize the flexible prosumers in reducing Q_DR. The cost for the BRP with the DR program becomes:

$$J_\text{BRP}^\text{DR} = -\pi_\text{C} \cdot \left(\sum_{v\in\mathcal{V}} q_v + \sum_{u\in\mathcal{U}} q_u \right) - \pi_\text{G} \sum_{v\in\mathcal{V}} q_v \cdot (1 - \alpha + \alpha \cdot Q_\text{DR}) + \pi^\star \cdot \frac{q - \tilde{q}}{|\sum_{u\in\mathcal{U}} q_u| + |Q_\text{w}|} \cdot Q_\text{w}. \tag{6}$$

The difference with (4) is that, in (6), part of the quantity $\pi_\text{G} \sum_{v\in\mathcal{V}} q_v$ is allocated for the DR program incentives; furthermore, the fraction $1 - Q_\text{DR}$ is effectively payed to the flexible consumers, as the DR program might only partially procure the required energy. Thanks to the incentive, the cost for the flexible consumer u becomes:

$$J_u^\text{DR} = J_u - \alpha \cdot (1 - Q_\text{DR}) \cdot \pi_\text{G} \sum_{v\in\mathcal{V}} q_v \cdot \frac{Q - q_u}{UQ - \sum_{u\in\mathcal{U}} q_u} \tag{7}$$

when $UQ \neq \sum_{u\in\mathcal{U}} q_u$, otherwise $J_u^\text{DR} = J_u$. Note that the incentive is weighted by the contribution of u to the DR program. We write the cost for the flexible consumers u, including the utility cost, as:

$$J_u^\star = J_u^\text{DR} - f(q_u).$$

The DR program aims to minimize the total cost for flexible consumers, but is challenged by the fact that the imbalance price and actual households consumption, $\pi^\star$ and $\sum_{v\in\mathcal{V}} q_v$, are unknown a priori. For this reason, in the following optimization the program uses the approximated values $\pi^\star = \tilde{\pi}^\star$ and $\sum_{v\in\mathcal{V}} q_v = \sum_{v\in\mathcal{V}} \tilde{q}_v$, respectively:

$$\min_{q_u, u\in\mathcal{U}} \sum_{u\in\mathcal{U}} J_u^\star \tag{8}$$

$$\text{s.t.}\ Q_\text{min} \leq q_u \leq Q, \tag{9}$$

$$0 \leq Q_\text{DR} \leq 1. \tag{10}$$

IV. Blockchain-Based Solution

We propose to use blockchains at both layers of the market, but with different purpose. At layer 1, a smart contract is used to increase the automation of the accounting mechanism, aiming at reducing its duration. At layer 2, a different smart contract supports the resolution of (8).

A. Layer 1

A smart contract, owned by the SO, is deployed on a blockchain for each STU. Only the addresses of qualified BRPs are entitled to modify its state. The functionalities of the contract, depicted in Fig. 4, are:

(F1) Receive a credit cover from each BRP. The credit cover is a mechanism used in the electricity market that prevents agents from not paying the future balancing cost [15].

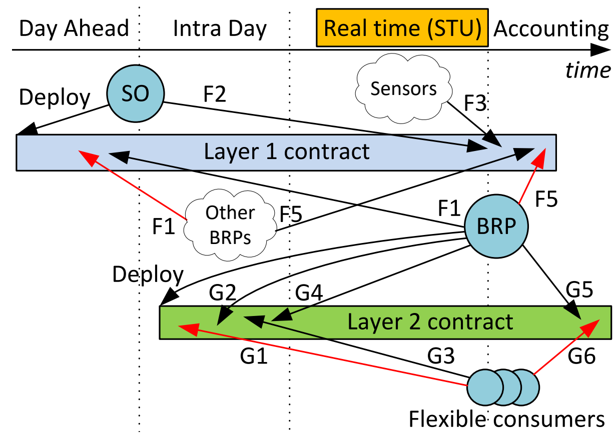


Fig. 4. Sequence of operations on the contracts during time. Red arrows indicate functions that transfer credit from/to the smart contracts.

(F2) After the STU, receive the list of activated balancing offers from the SO, with their corresponding cost.

(F3) Receive the metered generation/consumption. This function is used by the sensors, installed on the grid. We assume that the sensors do not show byzantine behavior, meaning that they timely send valid information.

(F4) Compute the price $\pi^\star$ for the STU, according to the German pricing formula ("reBAP") [6]. This function is called upon the reception of all the measurements.

(F5) Settle the imbalance position. Each BRP can use this function to receive the difference between the credit cover and the actual imbalance cost, see (1).

We briefly outline a qualitative comparison of the proposed approach with the state-of-art imbalances accounting mechanism. The proposed solution removes the burden of the accounting process, giving a negligible T_ACC. The availability and transparency of information are ensured by the observability of the blockchain from all the agents. Finally, this solution provides a seamless credit cover mechanism.

B. Layer 2

The resolution of the non-convex problem (8) is delegated to a flexible consumer $\hat{u} \in \mathcal{U}$, chosen randomly in each STU. A smart contract is used by the BRP to indicate $\hat{u}$ and to publish the information needed for the resolution of the problem; the delegated flexible consumer resolves the problem and publishes the result via the same smart contract.

The functionalities of the contract, also depicted in Fig. 4, are:

(G1) Receive, and store, the value of marginal utility, π_u, and credit cover from each $u \in \mathcal{U}$. Initialize $q_u = Q$, $u \in \mathcal{U}$.

(G2) Receive the values of $\tilde{\pi}^\star$, $\sum_{v\in\mathcal{V}} \tilde{q}_v$, Q_w and $\tilde{Q}_\text{w}$ from the BRP. In addition, receive the index $\hat{u}$ of the flexible consumer delegated to solve the problem. The information is stored in the state of the smart contract, and is available to all flexible consumers.

TABLE I
SIMULATION PARAMETERS

π_{C}	0.05 €/kWh	π_{G}	0.03 €/kWh
Q_{w}	500 kWh	$Q_{\min}$	0.925 kWh
σ_{h}	6	σ_{v}	15
Q	3.7 kWh	γ	0.01

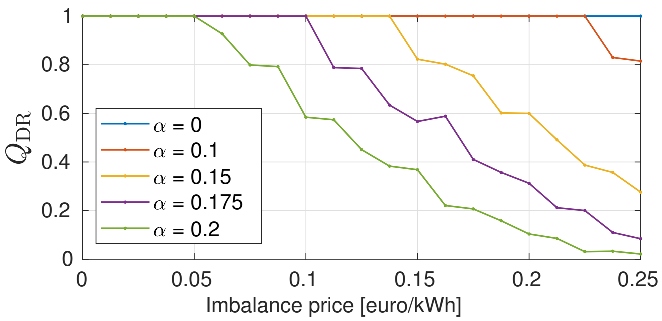


Fig. 5. Energy not balanced by the DR program.

(G3) Receive the result of (8), i.e. q_u, $\forall u \in \mathcal{U}$. This function can be only called by consumer $\hat{u}$, after the local resolution of the problem.

(G4) Destroy the contract. This function can only be called by the BRP, and it returns the credits to the corresponding flexible consumers. It entitles the BRP to not accept the flexibility offer, and is used in case that the solution is not profitable for the BRP.

(G5) Offload the cost from layer 1, according to the pricing scheme. This function is called by the BRP upon reception of metered consumption.

(G6) Settle the position of the flexible consumers using (7). This is called by each flexible consumer and causes the transfer of credit to its account.

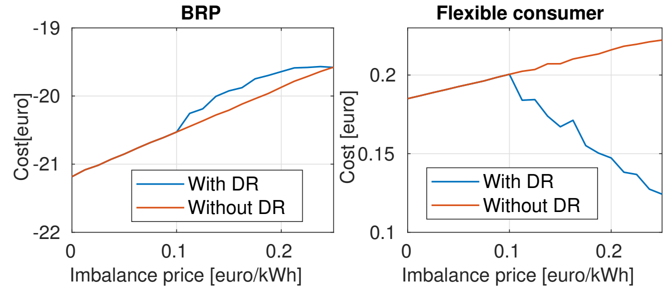
This solution permits a minimum intervention of the BRP in the DR program, as the only required actions are to deploy the smart contract and to provide the initial values, by means of (G2). At the same time, all the flexible consumers can audit the correctness of the resolution of the problem.

V. RESULTS

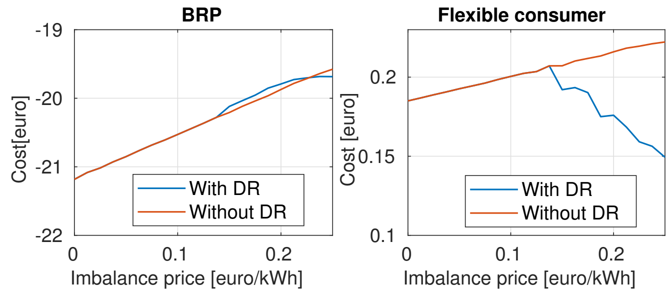
The results are obtained via numerical simulation of an example power grid. The smart contracts are implemented in Solidity, a programming language supported by Ethereum, and deployed on a private blockchain. The grid simulator interacts with the blockchain via a Node.js script.

A. Layer 2 simulation

We simulate a power system in which there are $V = 3500$ households, $U = 70$ EV charging stations acting as flexible consumers, and a small RES owned by the BRP. The system is parametrized as in Table I, while the forecasted load profiles of households and EVs are plotted in Fig. 3. The utility function of $u \in \mathcal{U}$ is characterized by the marginal price π_u, uniformly generated in $[0.20, 0.50]$ €/kWh.



(a)



(b)

Fig. 6. Cost comparison when (a) $\alpha = 0.175$ and (b) $\alpha = 0.15$.

First, we analyze the case in which flexible consumers are called to provide up-regulation in response to a deficit of 30 kWh, corresponding to $2\sigma_{\mathrm{h}}$, caused by the RES. Fig. 5 shows the amount of energy curtailed by the DR program as function of the imbalance price, for different values of the reward parameter α. When the reward increases, the flexible consumers are more stimulated to curtail their absorption.[2] In Fig. 6, we set $\alpha = 0.175$ and $\alpha = 0.15$ and compare the average cost for the agents, for different values of the imbalance price, in the cases with and without flexibility. The cost for the consumers is not reported, as they are exposed to a fixed price, see (2). Note that, as the imbalance cost increases, the flexible consumers decrease their consumptions, and therefore their cost. This also means that their EV will charge more slowly, see discussion in Sec. V-B. The figures also show that, from the BRP perspective, when $\alpha = 0.175$, the DR program is never beneficial, as the amount of credit allocated for the reward is too high and the reduction of income on selling energy too low, compared to the reduction of the imbalance cost due to the RES. On the other hand, when $\alpha = 0.15$, the DR program decreases the cost for the BRP, when the imbalance price is higher than 0.225 €/kWh. We remark that the results only consider positive imbalance prices, because the modeled system can only provide up-regulation.

In comparison with the standard implementations of DR programs [19], the proposed one offloads part of the operating cost from the BRP to the consumers. The operating cost of the blockchain-based DR program depends on the number of transactions that it requires, and on the fee associated

[2]This also reduces the margin of the BRP, but the optimal selection of α is not studied in this work.

with a transaction, that is decided by the agents that append blocks to the blockchain, see Sec. II-B. In a STU, the BRP sends only two transactions, corresponding to functions (G2) and (G5) of Sec. IV. The generic flexible consumers also send two transactions, see functions (G1) and (G6). However, the flexible consumer delegated to resolve the problem is required to send the values $q_u \, \forall u \in \mathcal{U}$, see (G3). To limit the amount of fee, to be payed for this transaction, this consumer only sends updates for those that operate curtailment, i.e. for which $q_u < Q$. Another option for the implementation of the blockchain-based DR program is to employ decentralized optimization algorithms [11], with the additional benefit that they also keep π_u private. However, compared to the proposed solution, they increase the amount of information exchanged to reach agreement, hence the number of transactions.

B. Integration with layer 1

We simulate the performance of the DR program under a variable imbalance price, over different STUs, based on the data set published by the operator TenneT, for the German market. In this country, the duration of a STU is 15 minutes. Fig. 7 reports the histogram of the price values during a period of one month (November 2017). Initially, we assume perfect knowledge of the price value, while the errors on the forecasted RES production and households consumption are randomly generated, according to the parameters reported in Table I. The DR program is executed, i.e. the smart contract is deployed, only for the STUs in which the price $\pi^\star$ is positive and the RES is expected to cause an energy deficit. In fact, this corresponds to the case of positive imbalance cost, see (1). The marginal utilities of flexible consumers are randomly generated, as in Sec. V-A, but kept fixed during the month. The design parameter α is set to 0.15.

The average gains for each agent, during the considered month, are showed in Table II. Columns "A" report the base cost of electricity, associated with the fixed price π_{C}; columns "B" the cost of imbalances and "C" the one of DR program, plus the gain associated to π_{G} in the case of the BRP. The DR program reduces the amount of electricity sold by the BRP, see the difference between columns "A", but compensates this loss with the reduction of the imbalance cost, see columns "B". However, in this case study, the BRP observes a negative gain, -697.26 €, due to the excessive amount of incentive payed to the flexible consumers, see columns "C". We also note that only the most flexible consumers, i.e. those with low marginal price π_u, take profit from the DR program, as they reduce their absorption and receive the reward, proportionally to the reduction. This reflects in a remarkable gain at the end of the month, see Table II. On the other hand, the average flexible consumer does not have a remarkable gain from the DR program. This is also the case for the inflexible consumers, as they are billed with fixed price.

Further, Fig. 8 shows that, during the considered month, flexible consumers with lower marginal price experience lower average cost of electricity for a STU. In this realization of the process, there are four flexible consumers (two have marginal utility 0.2 €), that are selected for the energy curtailment.

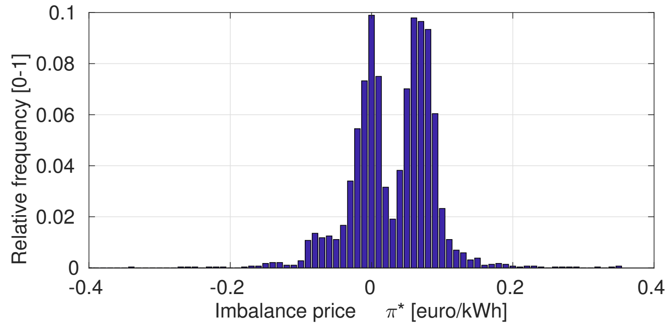


Fig. 7. Histogram of the observed imbalance price during one month, with bin size 0.01 €/kWh.

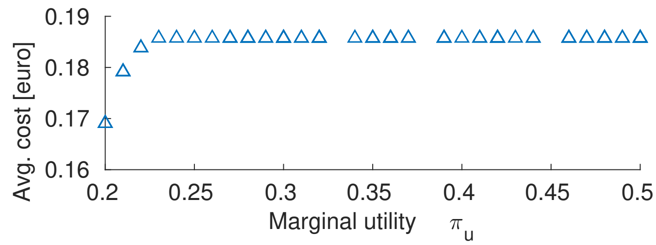


Fig. 8. Average cost as function of the marginal utility of flexible consumers.

Finally, we investigate the impact of delayed publication of imbalance price information on the layer 2 market dynamics. In Sec. III-C, we have modeled the estimation error on the imbalance price as a Gaussian variable with variance σ_{BM}. If the estimated value, $\tilde{\pi}^\star$, is negative, but the real value, $\pi^\star$, is positive, a false negative occurs: the BRP does not deploy the DR contract, missing the business opportunity for the flexible consumers. In contrast, when $\pi^\star < 0$ and $\tilde{\pi}^\star > 0$, i.e., when a false positive occurs, the DR contract is implemented even if the system needs down-regulation, causing a cost for both the BRP and the flexible consumers. Table III shows that, when this error increases, false positive and negative decisions increase. With the availability of perfect information, the BRP would have deployed a contract in the 75% of the STUs.

VI. Conclusion and Future Work

We have studied an implicit DR program, in which the BRP lowers its imbalance cost by leveraging on the flexibility of its consumers that are stimulated with incentives to lower the imbalance cost. We proposed to use blockchain smart contracts at two layers of the balancing market and discussed the benefits of this solution. At layer 1, a smart contract permitted to reduce the delay of publication of the imbalance price, causing a positive effect on the market dynamics of layer 2. The blockchain-based solution also satisfies the market facilitation criterion. The problem of implementing DR programs, with low operating cost for the BRP, has been solved by means of another smart contract at layer 2. Possible improvements to the scheme are (i) the adoption of decentralized optimization

TABLE II
COSTS DURING ONE MONTH

	Without flexibility [€]				With flexibility [€]				Gain [€]
	A	B	C	Total	A	B	C	Total	
BRP	-135940	-118.82	-59187	-195245.82	-135710	-305.56	-58533	-19454.85	-697.26
Avg. flex. consum.	532.80	-0.69	0	531.91	529.50	-2.11	-9.35	518.04	13.87
Most flex. consum.	532.80	-0.69	0	531.91	484.76	-2.13	-134.30	348.33	183.58
Less flex. consum.	532.80	-0.69	0	531.91	532.8	-2.11	0	530.69	1.22
Inflex. consum.				45.10				45.10	0

TABLE III
PERCENTAGE OF DECISIONAL ERRORS OF THE BRP DURING ONE MONTH

σ_{BM}	False negative [%]	False positive [%]
0.001	0.3	0.3
0.005	1.9	1.5
0.01	3.8	2.8
0.02	6.3	4.7

algorithms with fast convergence, to reduce the amount of information shared by consumers, while keeping low the operating cost, and (ii) the inclusion of the cost of sending transactions, i.e. their fee, in problem (8). Finally, the proposed scenario is characterized by absence of down-regulation. The future work should investigate the inclusion of new flexible consumers types, to increase their diversity and therefore the efficiency of the program.

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